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Cross-Borehole Electromagnetic Tomography – Scoping Study and Literature Review

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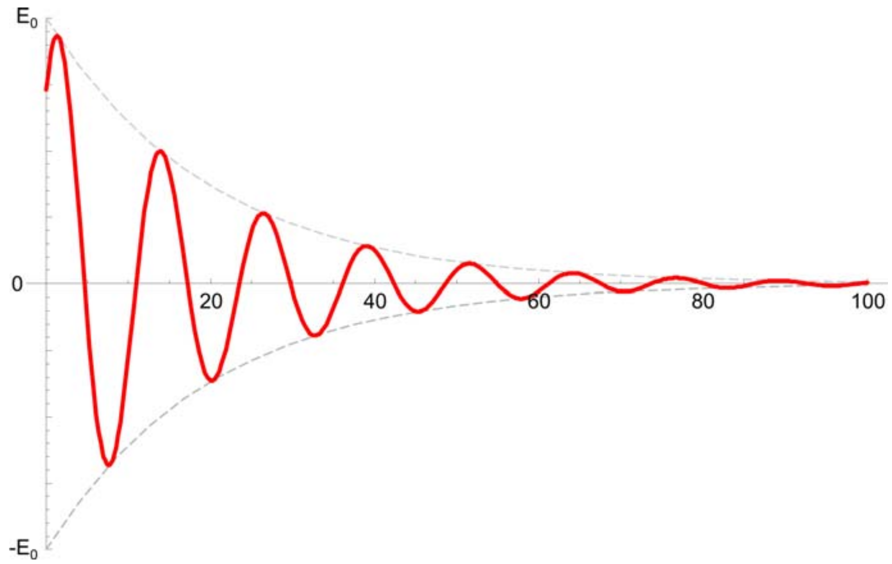

BRITISH GEOLOGICAL SURVEY

ELECTRICAL TOMOGRAPHY PROGRAMME

INTERNAL REPORT IR/05/146

Cross-Borehole Electromagnetic Tomography – Scoping Study and Literature Review

P B Wilkinson

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Electric field of an EM wave decaying with distance as it propagates in a conductive medium.

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Foreword

This report examines the basic principles of using intermediate frequency electromagnetic tomography in a cross-borehole configuration, highlights some of the issues involved, and reviews the literature relevant to this subject.

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Summary

Cross-borehole electromagnetic tomography is a non-contact geophysical method that can be used to generate images of the electrical properties of the subsurface. It is rather underutilised for site-scale investigation, due to the broad range of frequencies over which it must respond and the complicated nature of the electromagnetic fields in this range. However, such a system would find applications in a wide variety of environments, from fracture characterisation in highly resistive crystalline rock to pollution monitoring in conductive landfills. There is currently a gap in the European market for this type of tomography, despite the fact that it is in use and subject to on-going development in Canada, the U.S. and Australia. This report reviews the literature relevant to a cross-hole electromagnetic tomography imaging system and makes recommendations on its design and implementation.

1 Literature Review

Electromagnetic tomography (EMT) is a geophysical technique used to investigate the electrical properties of the subsurface. There are two commonly used ranges of frequency - audio magnetotellurics (up to a few tens of kHz, for depths up to a few kilometres) and ground penetrating radar (tens to hundreds of MHz, for depths of a few metres). The intermediate frequency range is somewhat under-utilised, especially in a cross-hole configuration. This is probably due to the more complicated nature of the electromagnetic fields at these frequencies. But there are many benefits to working in this regime; no galvanic contact is required with the formation, there is a good balance between resolution and depth of investigation, and resistivity and permittivity can be imaged simultaneously. Despite this, there is a gap in the market for this technology. During a recent commercial survey, no European contractor could be found to conduct a cross-hole EMT survey (Wilkinson *et al.*, 2004). This report examines the basic principles of designing, using and analysing intermediate frequency EMT in a cross-borehole configuration, highlights some of the issues involved, and reviews the literature relevant to this subject.

A schematic diagram of a cross-hole EMT system is shown in Fig. 1. It is envisaged that the typical depths and separation of the boreholes will be tens to hundreds of metres, making the system ideal for site-scale investigations. The targets to be imaged will lie on or near the panel between the boreholes. For the most part, it will be assumed that these targets will have different electrical properties with respect to the background, but the same magnetic properties. That is, there will be contrasts in resistivity (ρ) and/or permittivity ($\varepsilon = \varepsilon_0\varepsilon_r$), but not in permeability ($\mu = \mu_0\mu_r$). Any exceptions to these assumptions will be pointed out in the text.

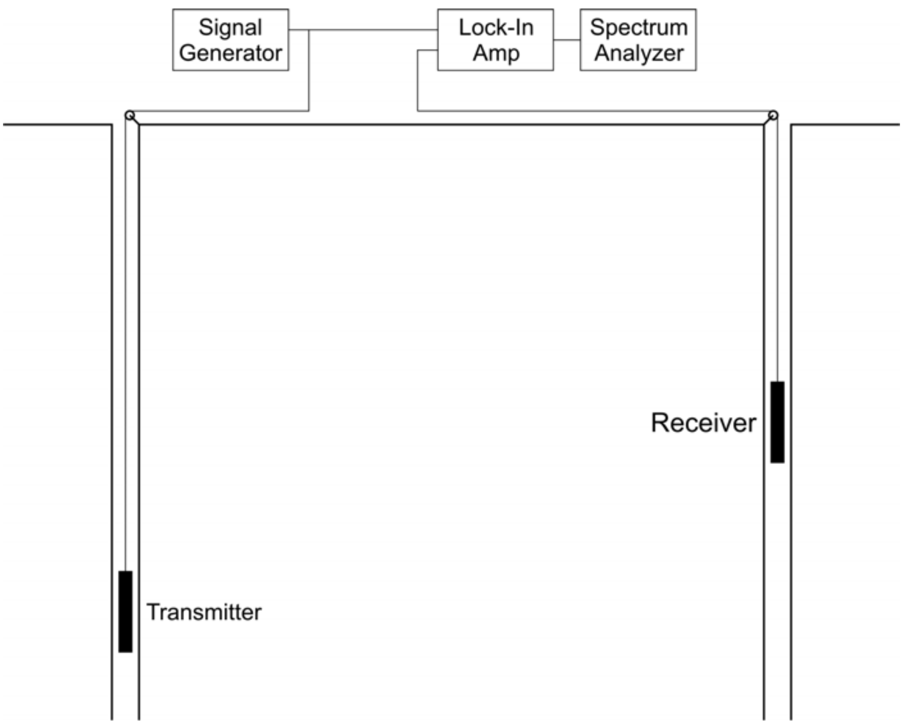

Figure 1: Schematic diagram of a crosshole EMT data acquisition system.

The character and propagation of EM waves in conductive media, such as geological formations, depends on the ratio of the magnitudes of the conduction current density and the displacement current density. This ratio is called the *dissipation* (D) and is given by

$$D = \frac{1}{\rho \omega \varepsilon}, \qquad (1)$$

where $\omega = 2\pi f$ is the angular frequency and f is the frequency. If $D << 1$, then the medium is a good dielectric and will support radiative waves, whereas if $D >> 1$, the medium is a good conductor and the EM waves will be heavily damped (they are sometimes called *diffusive* in this regime). Løseth *et al.* (2005) have demonstrated that, for $D > 10$, the evolution of the EM wave is dominated almost entirely by the resistivity and conversely by the permittivity for $D < 0.1$. In either of these regimes, EMT will only be sensitive to the changes in the dominant electrical property. However, in the intermediate regime, $0.1 < D < 10$, it should be possible to image contrasts in either property, though it is worth noting that permittivity contrasts between different rock types are generally much smaller than the corresponding resistivity contrasts. The largest permittivity contrasts tend to occur between rock and fractures or voids filled with air ($\varepsilon_r = 1$) or water ($\varepsilon_r \approx 80$). For a typical earth permittivity of $\varepsilon_r = 10$, Fig. 2 shows the frequencies for which $D = 0.1$, 1 and 10 as a function of resistivity. For frequencies below the red $D = 10$ line, conduction currents dominate and wave propagation is controlled by ρ. Above the green $D = 0.1$ line, wave propagation is dependent only on ε since the displacement currents are dominant.

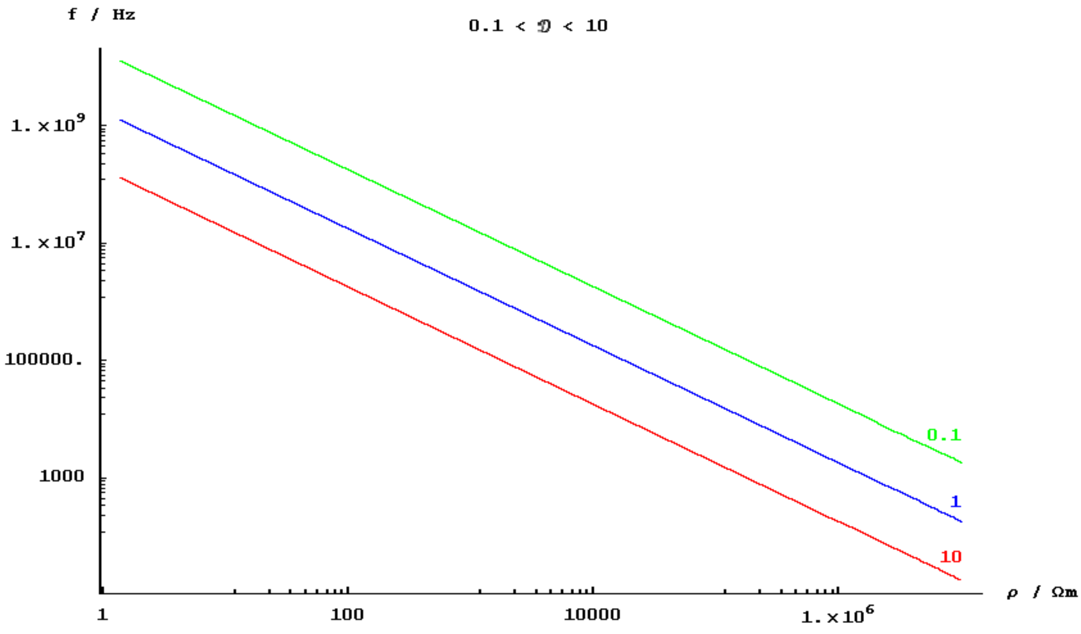

Figure 2: Log-Log plot of frequency vs resistivity showing $D = 0.1$ (green), $D = 1$ (blue) and $D = 10$ (red line).

The character of the EM waves can be illustrated by considering the simple case of a plane wave in an infinite conductive whole space. Assuming propagation along the x-axis, the electric field takes the form

$$\mathbf{E} = \mathbf{E}_0 \exp(-\alpha x) \exp i(\omega t - \beta x), \qquad (2)$$

where $\alpha = 1 / \delta$ and $\beta = 2\pi/\lambda$. δ is the skin depth, λ is the wavelength, and α and β are positive values given by

$$\alpha = \frac{\omega}{c_0}\left(\frac{\varepsilon_r \mu_r}{2}\right)^{1/2}\left(\left(1+D^2\right)^{1/2} - 1\right)^{1/2}, \tag{3}$$

and

$$\beta = \frac{\omega}{c_0}\left(\frac{\varepsilon_r \mu_r}{2}\right)^{1/2}\left(\left(1+D^2\right)^{1/2} + 1\right)^{1/2}, \tag{4}$$

respectively, where c_0 is the speed of light in vacuum. In the limit $D >> 1$ (low frequency or high conductivity), the skin depth reduces to the familiar form

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}. \tag{5}$$

For these heavily damped waves, the wavelength is proportional to the skin depth:

$$\lambda = 2\pi\delta. \tag{5}$$

In the opposite limit $D << 1$ (high frequency or high resistivity), the damping is light and the wavelength is simply given by

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r \mu_r}}, \tag{7}$$

as expected. The skin depth is

$$\delta = \frac{2\rho\sqrt{\varepsilon}}{\sqrt{\mu}}, \tag{8}$$

which, in this limit, is independent of frequency.

For most applications of cross-hole EMT, D is likely to be ≥ 1, so the wavelength will be larger than the skin depth (although in hard crystalline rocks, this could be reversed). For typical resistivities (10 – 1000 Ωm) and frequencies (10 kHz – 1 MHz), this will result in skin depths of ~10 – 100 m, comparable with the borehole spacings. In this case, one will be considering the near-field of the antenna where the waves will not be planar. A full description of the attenuated waves from an antenna in a conductive medium is given in Løseth *et al.* (2005), but enough insight into the character of the fields can be gained from the undamped case of a small electric (Hertzian) dipole in free space. Its electric field has components that depend on the distance from the dipole, r, as $1/r$, $1/r^2$ and $1/r^3$, whilst the magnetic field components are proportional to $1/r$ and $1/r^2$ only. The $1/r$ terms are the *radiation* fields, which carry energy away from the dipole. The $1/r^2$ terms are known as *induction* fields, which store energy from the antenna in one quarter-cycle and return it in the next. Finally, the $1/r^3$ electric field is called the *quasi-static* field, which arises due to charge moving to and from the ends of the antenna. At a distance of $r = \lambda/2\pi$, all three types of field are equal in magnitude. When $r < \lambda/2\pi$, the quasi-static and induction fields dominate, this is the *near-field* region. The *far-field* region occurs where $r > \lambda/2\pi$ and the radiation fields are dominant. Capacitive resistivity imaging (CRI) is an example of a low-frequency geoelectrical imaging system that works in the extreme near-field, the quasi-static regime, only (Kuras *et al.*, 2005). By contrast, ground penetrating radar (GPR) is a high frequency system that detects the far-field radiating waves (Olsson *et al.*, 1992). However, a radio-frequency cross-hole EMT system is likely to operate around the $r = \lambda/2\pi$ region, depending on the electrical properties of the ground and the frequency, and will therefore have to be able to detect and analyse combinations of all three types of field. This will require innovative designs of transmitters, receivers and forward and inverse modelling algorithms.

Whilst low- and high-frequency EM imaging are both commonly used (see Spies (1996) for a comprehensive review), there are only a few systems that exploit the intermediate regimes of diffusive and radio-frequency EMT. Specifically these are the Radio Imaging Method (RIM), the Very Early Time Electromagnetic (VETEM) system and a modified RIM system from Petros Eikon Inc. RIM is a cross-hole system developed in the 1980s by mining companies to map coal seams for continuity and detect disruptions (Stolarczyk & Stolarczyk, 1998). It has been shown to be complementary to the In-Seam Seismic method, but faster and more convenient with better resolution (Vozoff *et al.*, 1993). It has also been shown to be effective in detecting and imaging mineral deposits due to the attenuation of the signal caused by conductive ores (Thomson *et al.*, 1992; Thomson & Hinde, 1993; van Schoor & Duvenhage, 1999).

VETEM is a towed surface system being developed by the US Geological Survey for monitoring shallow nuclear waste repositories. For example, at the DoE Radioactive Waste Management Complex at Idaho Falls, a 1 acre site consisting of a 2.5 m deep layer of waste covered by ~1.5 m of soil is being monitored by a prototype VETEM system (Wang *et al.*, 2004). The system uses a rapidly ramped broadband signal over the range 0-5 MHz, which gives high resolution in the shallow sub-surface, like GPR, with better imaging of deeper layers (Cui *et al.*, 2003). Further technical details can be found in Abraham *et al.* (2003). Since evanescent waves are included in the data analysis, sub-wavelength resolution is possible, by analogy with the recently discovered "perfect lens" phenomenon in optics (Pendry, 2000).

Petros Eikon Inc of Canada has developed a substantially modified RIM-type system for mining, geotechnical and environmental cross-hole investigations. It can operate over a broad frequency range (a few tens of kHz to a few MHz) using the same antenna. For simple dipole antennae, transmission and reception are most efficient when the length of the dipole is $\lambda/2$. However, for the typical frequencies and resistivities encountered, the wavelength can be over 100m, making the dipole antenna prohibitively long for borehole use. To overcome this limitation, and to improve resolution, Petros Eikon use a Normal Mode Helical Antenna (Groom, 2001), a compact design used in mobile phones. Whilst this antenna is not an efficient radiator, in tests it has been found to be effective in the near field. A further advantage is that it has a very broad resonance response, enabling it to be used over a large frequency range. Since the antenna is essentially a combination of a magnetic coil and an electric dipole, it creates magnetostatic fields in addition to electrostatic fields. These fields will also couple to the helical receiver and must be accounted for in the data analysis.

The different properties of the rock types affect the measured fields in different ways. In the diffusive regime (large D), the resistivity controls both parameters of the EM waves (Yu & Edwards, 1997). The first parameter is the rate of damping, which affects the amplitude of the received signal. The second is the speed of propagation, which controls the time-of-flight of the signal when measuring in the time-domain (Coen, 2000), or the phase shift in the frequency-domain. In this limit, the permittivity has no effect. Conversely, if the dissipation is small, the speed of the wave is controlled solely by the permittivity (and permeability if applicable), whereas the damping is affected by both resistivity and permittivity. In the intermediate regime where $D \approx 1$, both parameters contribute to both properties (Yu *et al.*, 1998).

Many approaches to inversion of measured EM data have been proposed and assessed. These fall broadly into two camps: rapid approximate techniques based on ray tracing, and more numerical methods involving full non-linear inversion. Intuitively, one would expect ray-tracing techniques to work only in the high frequency, propagating wave limit. But many studies have demonstrated that they are also valid for the diffusive waves found in the low and intermediate frequency regimes. This has been shown from the standpoints of theory (Coen, 2000; Lee *et al.*, 2002; Løseth *et al.*, 2005), modelling studies (Nekut, 1994) and field data (Rogers *et al.*, 1993; van Schoor & Duvenhage, 1999). Despite these successes, non-linear inversion techniques have also been developed, which cope better with the effects of large property contrasts. Initially such techniques were based on integral equation techniques and the Born approximation (Sena & Toksöz, 1990; Alumbaugh & Morrison, 1995a; 1995b; 1995c), with better results in high contrast regions being obtained by using higher order terms in the Born series expansion

(Abubakar & van den Berg, 2000a; 2000b; Zhang & Liu, 2001; Tseng *et al.*, 2003). However, rapid advances in available computer power have also made it possible to use finite-difference methods to calculate the fields numerically at each stage of the inversion. This has been demonstrated in both the time-domain (Debroux, 1996; Yu *et al.*, 1998) and the frequency domain (Dorn *et al.*, 1999; Champagne *et al*., 2001). There are also methods that combine some advantages of the differential and integral equation techniques (Newman, 1995; Xie *et al.*, 2000).

The resolution of an EMT image depends on the frequency as well as the accuracy of the inversion method. Since they operate in the far-field, the resolution of high-frequency EMT techniques is roughly equal to the wavelength (Olsson *et al.*, 1992). For lower frequency near-field applications, the resolution depends on the data coverage, the number of different frequencies in use (Cao *et al.*, 2003) and the spatial sensitivity of each measurement configuration (Spies & Habashy, 1995). The resolution has been shown to be significantly better than a wavelength in this regime (Zhou *et al.*, 1993; Alumbaugh & Morrison, 1995a; Xie *et al.*, 2000). This should not be a surprising result to those familiar with DC resistivity tomography or induced polarisation tomography, since these techniques also produce sub-wavelength resolution.

The design and production of a prototype EMT system will depend critically on the following considerations (amongst others):

• <u>Design of the antenna</u>. Since Petros Eikon has had considerable success using a compact helical antenna (Groom, 2001), this would seem an ideal place to start. A possible improvement would be to investigate the spiro-helical antenna, a tight helix wound into a looser spiral, which shares the advantages of the helical antenna whilst being about three times smaller (Ghoreishian, 1999). Another possibility would be to use a compact fractal antenna (Puente *et al.*, 1998). For accurate tomographic imaging, the radiation patterns of the antenna in typical rock types will have to be calculated (Ellefsen *et al.*, 2004; Ellefsen & Wright, 2005).

• <u>Frequency range / time- or frequency-domain</u>. To cover the widest range of applications, it would be advisable for the system to be able to operate over a broad bandwidth. The literature indicates that transient (pulsed) time-domain systems are harder to design and engineer than continuous frequency-domain systems (Wilt *et al.*, 1995a; 1995b; or compare the development of the RIM and VETEM systems).

• <u>Envisaged applications</u>. If a broad bandwidth is used, then cross-hole EMT will have a range of possible applications. With a compact antenna it will be applicable to geotechnical, environmental and engineering site investigations at low frequenices, e.g. for tunnel (Mahrer & List, 1995) and mineshaft detection, or contamination and groundwater investigation (Groom, 2001). Typically GPR would fail in these situations due to its short skin depth in relatively conductive ground (Wilkinson *et al.*, 2004). At frequencies of ~100 kHz – 1 MHz, EMT would be of use in detecting and characterising fracture zones in crystalline rock masses at larger distances than GPR (Day-Lewis *et al.*, 2003), although without the detailed orientation information provided by GPR reflectivity measurements (Olsson *et al.*, 1992). If hydraulic connectivity of fracture zones could be demonstrated (perhaps by the injection and mapping of conductive saline tracers), this technique could prove attractive to Nirex for post-closure monitoring of deep nuclear waste repositories (White *et al.*, 2004).

In summary, a cross-hole EMT system working in the intermediate frequency range would have the flexibility to be used in a wide variety of investigations. Most of the effort required on the hardware development would probably focus on antenna design and robustness of the system in the presence of noise. On the analysis side, a simple image reconstruction based on ray-tracing could be developed quickly for a testing with a prototype system. This would then serve as a starting point for a full non-linear inversion algorithm required for accurate tomographic imaging.

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